FUNCTION GENERATOR
AND TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR

BACKGROUND OF THE INVENTION

The present invention relates to a function generator suitable for temperature compensation of crystal oscillation frequency and a temperature compensated crystal oscillator using the function generator.

Various electronic equipments are required not only to be compact and light but also have high reliability and high accuracy these days. In such a background, a crystal resonator is widely used for generating a clock signal or the like in a large number of electronic equipments. The oscillation frequency of a crystal oscillating circuit using a crystal resonator is desired to be highly stable particularly against variation of the ambient temperature. An AT-cut quartz resonator is now the most commonly utilized as the crystal resonator.

It is known that the oscillation frequency of a crystal oscillating circuit using a crystal resonator is largely varied in accordance with the variation of the ambient temperature **Ta** when the temperature is not compensated. For example, the proportion of an oscillation frequency **Fa** (at the ambient temperature **Ta**) to a reference frequency **Fr** (at a reference temperature **Tr**) is varied by several tens ppm in accordance with the variation of the ambient temperature **Ta** ranging between –30 C° and +80 C°. Also, the reference frequency **Fr** fluctuates. Such variation and fluctuation of the oscillation frequency can be a significant problem in an electronic equipment with high accuracy. Accordingly, there is a demand for a crystal oscillating circuit with a more stable oscillation frequency. For example, it is necessary to suppress the variation in the frequency proportion Fa/Fr to 2.5 ppm or less and the fluctuation of the reference frequency **Fr** to 0.3 ppm or less.

In the electronic equipment with high accuracy, therefore, temperature compensation for the crystal oscillation frequency is generally effected. For example, the crystal resonator is connected with a variable capacitance diode in series, and a compensation voltage in accordance with the ambient temperature **Ta** is applied to the variable capacitance diode.

In a conventional technique, where N is 1 or a larger integer, a constant current unaffected by the ambient temperature **Ta** is made to flow to a series circuit of N diodes, a current in proportion to the difference between the ambient temperature **Ta** and the reference temperature **Tr** is made to flow to a series circuit of N+1 diodes, and a difference between voltages generated in the above-described circuits is applied between the base and the emitter of an output transistor. Thus, a current in proportion of the N+1th power of Ta – Tr is generated in the collector of the output transistor. If, assuming that N=2, a current in proportion to the cube of Ta – Tr is generated and a compensation voltage to be applied to a variable capacitance diode is generated from the current, third order temperature compensation can be achieved (see United States Patent No. 5,719,533).

For equipment requiring even higher accuracy with respect to temperature compensation, a high order control technique such as a fourth-order or fifth-order control technique is necessary (Japanese Unexamined Patent Publication No. 2003-8386).

To form a cubic function generator in the conventional technique in which a diode series is used, a supply voltage which can drive a series circuit of three diodes is necessary. Moreover, a driving voltage for four diodes and a driving voltage for five diodes are required for forming a fourth-order function generator and a fifth-order function generator, respectively.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a function generator and a temperature compensated crystal oscillating circuit which are operable at a low voltage to reduce power consumption of portable equipment represented by a cellular phone.

To achieve the object, according to the present invention, two or more current exchanger circuits are cascaded to form a cubic or higher order function generator. Each of the current exchanger circuits has the function of receiving, where n is 1 or a larger integer, a current in proportion to the nth power of a difference between the ambient temperature **Ta** and the reference temperature **Tr** and outputting a current in proportion to the n+1th or 2nth power of Ta – Tr.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram illustrating a temperature compensated crystal oscillator according to the present invention.

FIG. **2** is a block diagram illustrating the internal configuration of a linear function generator of FIG. **1**.

FIG. **3** is a circuit diagram illustrating the detailed configuration of a band-gap type current/voltage generator of FIG. **2**.

FIG. **4** is a circuit diagram illustrating the detailed configuration of a first current supplying circuit of FIG. **2**.

FIG. **5** is a circuit diagram illustrating the detailed configuration of a second current supplying circuit of FIG. **2**.

FIG. **6** is a circuit diagram illustrating the detailed configuration of a third current supplying circuit of FIG. **2**.

FIG. **7** is a circuit diagram illustrating the detailed configuration of a fourth current supplying circuit of FIG. **2**.

FIG. **8** is a circuit diagram illustrating the detailed configuration of a zero-order function generator of FIG. **1**.

FIG. **9** is a circuit diagram illustrating the detailed configuration of a cubic function generator of FIG. **1**.

FIGS. **10A** and **10B** are circuit diagrams illustrating configurations in which each diode in a first current exchanger circuit of FIG. **9** has a transistor configuration.

FIGS. **11A** and **11B** are circuit diagrams illustrating configurations in which each diode in a third current exchanger circuit of FIG. **9** has a transistor configuration.

FIG. **12** is a circuit diagram illustrating the detailed configuration of a fifth-order function generator of FIG. **1**.

FIG. **13** is a circuit diagram illustrating the detailed configuration of a crystal oscillating circuit of FIG. **1**.

FIG. **14** is a circuit diagram illustrating the detailed configuration of a fourth-order function generator which can be added to the temperature compensated oscillator of FIG. **1**.

FIG. **15** is a circuit diagram illustrating a modified example of the cubic function generator of FIG. **9**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** shows an exemplified configuration of a compensated temperature crystal oscillator according to the present invention. The compensated temperature crystal oscillator of FIG. **1** includes a controller **100**, a linear function generator **200**, a zero-order function generator **300**, a cubic function generator **400**, a fifth-order function generator **500**, two resistors **111** and **112**, a variable capacitance diode **113** and a crystal oscillating circuit **600**. Herein, where **Tr** is a reference temperature, a compensation voltage **Vin** to

be applied to the variable capacitance diode **113** so that the oscillation frequency of the crystal oscillating circuit **600** is constant regardless of an ambient temperature **Ta** is given as Formula 1.

[Formula 1]

$$Vin = -A(Ta - Tr)^5 - B(Ta - Tr)^3 + C(Ta - Tr) + D$$

where each of **A**, **B**, **C** and **D** is a constant other than 0.

The controller **100** is a shift register including twenty-seven flip-flops. The controller **100** receives an input of a serial data signal **Din** and a shift clock signal **CLK** and supplies signals corresponding to the four constants **A**, **B**, **C** and **D** in Formula 1 and the reference temperature **Tr**. Signals **A**, **B**, **C**, **D** and **Tr** are four bits, four bits, six bits, eight bits and five bits, respectively.

In response to the signals **A**, **B**, **C**, **D** and **Tr**, the linear function generator **200** performs the following functions: The function of supplying a constant base voltage **Vbc** unaffected by the ambient temperature **Ta**; the function of current sources **Ic1** and **Ic3** for discharging a constant current unaffected by the ambient temperature **Ta**; the function of current sources **Ic2** and **Ic4** for absorbing a constant current unaffected by the ambient temperature **Ta**; the function of current sources **It1**, **It2** and **It3** for discharging a current in proportion to $Ta - Tr$ in the case of $Ta \geq Tr$ and absorbing a current in proportion to $|Ta - Tr|$ in the case of $Ta < Tr$.

The cubic function generator **400** connected to the current sources **Ic1**, **Ic2** and **It1** generates a bidirectional current **It4** in proportion to the cube of $Ta - Tr$ in the case of $Ta \geq Tr$ and in proportion to the cube of $|Ta - Tr|$ in the case of $Ta < Tr$.

The fifth-order function generator **500** connected to the current sources **Ic3**, **Ic4** and **It2** generates a bidirectional current **It5** in proportion to the fifth power of $Ta - Tr$ in the case of $Ta \geq Tr$ and in proportion to the fifth power of $|Ta - Tr|$ in the case of $Ta < Tr$.

The zero-order function generator **300** receives the base voltage **Vbc** and the signal **D** and generates a constant voltage **Vc** regardless of the ambient temperature **Ta**.

A series circuit including the two resistors **111** and **112** and the variable capacitance diode **113** constitutes means for converting the sum of an output current **It3** of the linear function generator **200**, an output current **It4** of the cubic function generator **400** and an output current **It5** of the fifth function generator **500** into a voltage and supplying as a compensation voltage **Vin** the sum of the voltage resulting from the conversion and an output voltage **Vc** of the zero-order function generator **300** to the crystal oscillating circuit **600**. The compensation voltage **Vin** can be given by Formula 1. A voltage **Vout** is an output voltage of the crystal oscillating circuit **600**.

FIG. **2** shows the internal configuration of the linear function generator **200**. The linear function generator **200** includes a band-gap type current/voltage generator **250**, a first current supplying circuit **260**, a second current supplying circuit **270**, a third current supplying circuit **280**, and a fourth current supplying circuit **290**.

FIG. **3** shows the detailed configuration of the band-gap type current/voltage generator **250**. The band-gap type current/voltage generator **250** of FIG. **3** includes two PNP transistors **251** and **257**, five NPN transistors **252**, **253**, **254**, **255** and **259**, and two resistors **256** and **258**. A voltage **Vbt** is a base voltage for transferring a current represented by a linear function of the ambient temperature **Ta**, a current **It** is a current increasing in proportion to the ambient temperature **Ta**, and a voltage **Vt** is a voltage increasing in proportion to the ambient temperature **Ta**.

FIG. **4** shows the detailed configuration of the first current supplying circuit **260**. The first current supplying circuit **260** of FIG. **4** includes an operational amplifier **261**, an NPN transistor **262**, a resistor **263**, and a PNP transistor **264**. The base voltage **Vbc** of the PNP transistor **264** is used for transferring a constant collector current unaffected to the

ambient temperature **Ta**. The first current supplying circuit **260** of FIG. **4** further includes, correspondingly to the five bits of the signal **Tr**, five PNP transistors **265** sharing the base voltage **Vbc**, two current output circuit **266** and **267**, five PNP transistors **268** for current feedback to the emitter of the NPN transistor **262**, and five NPN transistors **269** for switching. When the number of ON transistors among the five NPN transistors **269** is changed in response to the signal **Tr** of five bits, each of the currents **Ic1**, **Ic2**, **Ic3** and **Ic4** is varied in accordance with the changed number of the ON transistors.

FIG. **5** shows the detailed configuration of the second current supplying circuit **270**. The second current supplying circuit **270** of FIG. **5** includes, correspondingly to the four bits of the signal **A**, four PNP transistors **271** sharing the base voltage **Vbt**, four PNP transistors **272** for discharging a current, four NPN transistors **273** for switching, four PNP transistors **274** sharing the base voltage **Vbc**, eight NPN transistors **275** together forming four current mirror circuits for absorbing a current, and four NPN transistors **276** for switching. When the number of ON transistors among the four NPN transistors **273** and the number of ON transistors among the four transistors **276** are changed in response to the signal **A** of four bits, the current **It2** is varied in accordance with the changed number of the ON transistors.

FIG. **6** shows the detailed configuration of the third current supplying circuit **280**. The third current supplying circuit **280** of FIG. **6** includes, correspondingly to the four bits of the signal **B**, four PNP transistors **281** sharing the base voltage **Vbt**, four PNP transistors **282** for discharging a current, four NPN transistors **283** for switching, four PNP transistors **284** sharing the base voltage **Vbc**, eight NPN transistors **285** together forming four current mirror circuits for absorbing a current, and four NPN transistors **286** for switching. When the number of ON transistors among the four NPN transistors **283** and the number of ON transistors among the four NPN transistors **286** are changed in response to the signal **B** of

four bits, the current **It1** is varied in accordance with the changed number of the ON transistors.

FIG. **7** shows the detailed configuration of the fourth current supplying circuit **290**. The fourth current supplying circuit **290** of FIG. **7** includes, correspondingly to the six bits of the signal **C**, six PNP transistors **291** sharing the base voltage **Vbt**, six PNP transistors **292** for discharging a current, six NPN transistors **293** for switching, six PNP transistors **294** sharing the base voltage **Vbc**, twelve NPN transistors **295** together forming six current mirror circuits for absorbing a current, and six NPN transistors **296** for switching. When the number of ON transistors among the six NPN transistors **293** and the number of ON transistors among the six NPN transistors **296** are changed in response to the signal **C** of six bits, the current **It3** is varied in accordance with the changed number of the ON transistors.

FIG. **8** shows the detailed configuration of the zero-order function generator **300** of FIG. **1**. The zero-order function generator **300** of FIG. **8** includes a current source consisting of, correspondingly to the eight bits of the signal **D**, eight PNP transistors **301** sharing the base voltage **Vbc**, eight PNP transistors **302** for discharging a current, and eight NPN transistors **303** for switching. The zero-order function generator **300** of FIG. **8** further includes an NPN transistor **304** for supplying a constant voltage **Vc** regardless of the ambient temperature **Ta**, two resistors **305** and **306**, and a constant voltage supply **307**. When the number of the ON transistors among the eight NPN transistor **303** is changed in response to the signal **D** of eight bits, the voltage **Vc** is varied in accordance with the changed number of the ON transistors.

FIG. **9** shows the detailed configuration of the cubic function generator **400** of FIG. **1**. The cubic function generator **400** of FIG. **9** includes a first current exchanger circuit **410**, a second current exchanger circuit **420**, a third current exchanger circuit **430**, and a

fourth current exchanger circuit **440**. The first current exchanger circuit **410** is a quadratic function generator obtained where N = 1 holds in the conventional technique and includes three diodes **11**, **12** and **13**, an operational amplifier **14**, and an NPN transistor **15**. The second current exchanger circuit **420** is a current mirror circuit including three PNP transistors **31**, **32** and **33**, two NPN transistors **34** and **35**, three resistors **Rt1**, **Rt2** and **Rc**. The third current exchanger circuit **430** is a complementary circuit of the first current exchanger circuit **410** and includes three diodes **41**, **42** and **43**, an operational amplifier **44**, and a PNP transistor **45**. The fourth current exchanger circuit **440** is a complementary circuit of the second current exchanger circuit **420** and includes three NPN transistors **61**, **62** and **63**, two PNP transistors **64** and **65**, and three resistors **Rt1**, **Rt2** and **Rc**.

When Ta ≥ Tr, in the first current exchanger circuit **410**, the current **It1** flows into a series of diodes **11** and **12** to generate a voltage at the anode of the diode **11**. While the generated voltage is given to the base of the NPN transistor **15**, a voltage generated in the diode **13** is given to the emitter of the NPN transistor **15** via the operational amplifier **14**.

Here, a current value for the current source **Ic1** is indicated as a constant **Ir**, the voltage at the anode of the diode **13** is indicated as **V13**, and the voltage at the anode of the series of diodes **11** and **12** is indicated as **V11**. Also, the saturation current of each of the diodes and transistors is indicated as **Is**. In this case, the following formulas hold.

[Formula 2]

$$V13 = Vth \times \ln (Ir/Is)$$

[Formula 3]

$$V11 = 2 \times Vth \times \ln (It1/Is)$$

[Formula 4]

$$Vth = k \times Ta/q$$

where **k** indicates the Bolzmann's constant and **q** indicates the charge amount of an

electron. Also, when the collector current of the NPN transistor **15** is indicated as **I15**, the following formula can be obtained.

[Formula 5]

$$I15 = Is \times \exp\{(V11 - V13)/Vth\}$$

Thus, based on Formulas 2, 3 and 5, the following formula can be obtained.

[Formula 6]

$$I15 = Ir \times (It1/Ir)^2$$

Also, assumed that the current **It1** satisfies the following formula.

[Formula 7]

$$It1 = Ir \times \{(Ta - Tr)/Tr\}$$

When the current **It1** is supplied, the following formula can be obtained.

[Formula 8]

$$I15 = Ir \times \{(Ta - Tr)/Tr\}^2$$

Similarly, when Ta $\geq$Tr, in the second current exchanger circuit **420**, a voltage corresponding to a value for the collector current **I15** of the NPN transistor **15** is generated at each of the bases of the PNP transistors **31**, **32** and **33**, and then a current corresponding to the generated voltages flows from the collectors of the PNP transistors **32** and **33**. Then, owing to an operation of the NPN transistor **34**, a current of a value corresponding to the collector current of the PNP transistor **32** flows into the collector of the NPN transistor **35**. A current resulting from a difference between the collector current value of the PNP transistor **33** and the collector current value of the NPN transistor **35** is generated at an output terminal of the cubic function generator **400**.

In this case, the resistors **Rt1** and **Rt2** inserted and connected between a power source terminal **Vcc** and the emitter of the PNP transistor **31** and between the power source terminal **Vcc** and the emitter of the PNP transistor **32**, respectively, have a first temperature

coefficient, and the resistor **Rc** inserted and connected between the power source terminal **Vcc** and the emitter of the PNP transistor **33** has a second temperature coefficient. When the resistor **Rc** is formed of polysilicon, a resistance value for the resistor **Rc** can be made constant regardless of the ambient temperature **Ta**. On the other hand, when each of the resistors **Rt1** and **Rt2** is formed of a diffused resistor, the temperature coefficient of a resistance value **Rt** of the resistors **Rt1** and **Rt2** can be represented by the linear function of Ta – Tr. That is to say, with a constant **a**, the following formula holds.

[Formula 9]

$$Rt/Rc = 1 + a \times (Ta - Tr)$$

The constant **a** is several thousands ppm/°C. Accordingly, when the respective collector currents of the PNP transistor **33** and the NPN transistor **35** are indicated as **I33** and **I35**, respectively, the following formulas are obtained.

[Formula 10]

$$I33 = I15 \times Rt/Rc$$

[Formula 11]

$$I35 = I15$$

[Formula 12]

$$It4 = I33 - I35$$

Thus, the following formula holds.

[Formula 13]

$$It4 = Ir \times Tr \times a\ \{(Ta - Tr)/Tr\}^3$$

That is to say, the output current **It4** of the second current exchanger circuit **420** is a current in proportion to the cube of Ta – Tr.

Similarly, when Ta < Tr, the third and fourth current exchanger circuits **430** and **440** are operated, so that a current in proportion to the cube of |Ta – Tr| can be obtained as

the output current **It4** of the fourth current exchanger circuit **440**.

FIGS. **10A** and **10B** are circuit diagrams illustrating configurations in which each of the diodes **11**, **12** and **13** in the first current exchanger circuit **410** of FIG. **9** has a transistor configuration. In FIG. **10A**, the base and collector of a PNP transistor **12a** are grounded, the emitter of the PNP transistor **12a** is connected to the base of another PNP transistor **11a**, and the current **It1** is applied to the respective emitters of the PNP transistors **11a** and **12a**. In FIG. **10B**, the emitter of the PNP transistor **13a** is operated as the anode and a common connection section of the collector and base of the PNP transistor **13a** is operated as a cathode. Thus, the sum of the respective base/emitter voltages **Vbe11** and **Vbe12** of the two PNP transistors **11a** and **12a** corresponding to the current value of the power source **It1** is regarded as a voltage for two diodes. Also, the base/emitter voltage **Vbe13** of the PNP transistor **13a** corresponding to the current value of the power source **Ic1** is regarded as a voltage for one diode.

FIGS. **11A** and **11B** are circuit diagrams illustrating configurations in which each of diodes **41**, **42** and **43** in the second current exchanger circuit **430** of FIG. **9** has a transistor configuration. In FIG. **11A**, the base and collector of an NPN transistor **42a** are connected to the power source **Vcc**, the emitter of the NPN transistor **42a** is connected to the base of another NPN transistor **41a**, and the current **It1** is made to flow from each of the emitters of the NPN transistors **41a** and **42a**. In FIG. **11B**, the emitter of an NPN transistor **43a** is operated as the cathode and a common connection section of the collector and base of the NPN transistor **43a** is operated as the anode. Thus, the sum of the respective base/emitter voltages **Vbe41** and **Vbe42** of the two NPN transistors **41a** and **42a** corresponding to the current value of the power source **It1** is regarded as a voltage for two diodes. Also, the base/emitter voltage **Vbe43** of the NPN transistor **43a** corresponding to the current value of the power source **Ic2** is regarded as a voltage for one diode.

Note that the respective emitter currents **It1** of the two PNP transistors **11a** and **12a** in FIG. **10A** are supplied from two third current supplying circuits **280** which have been provided here, respectively. The respective emitter currents **It1** of the two NPN transistors **41a** and **42a** in FIG. **11A** are also supplied from the two third current supplying circuits **280**, respectively.

FIG. **12** shows the detailed configuration of the fifth-order function generator **500** of FIG. **1**. The fifth-order function generator **500** of FIG. **12** includes a first current exchanger circuit **510**, a second current exchanger circuit **520**, a third exchanger circuit **530**, a fourth current exchanger circuit **540**, a fifth current exchanger circuit **550**, and a sixth current exchanger circuit **560**. The respective configurations of the first, third, fourth and sixth exchanger circuits **510**, **530**, **540** and **560** are the same as those of the first, second, third and fourth current exchanger circuits **410**, **420**, **430** and **440**, respectively. The second current exchanger circuit **520** of FIG. **12** includes two PNP transistors **21** and **22**, two diodes **23** and **24**, an operational amplifier **25**, and an NPN transistor **26**. The fifth current exchanger circuit **550** is a complementary circuit of the second current exchanger circuit **520** and includes two NPN transistors **51** and **52**, two diodes **53** and **54**, an operational amplifier **55**, and a PNP transistor **56**.

When $Ta \geq Tr$, the collector current **I15** of the NPN transistor **15** in the first current exchanger circuit **510** is a current in proportion to the square of $Ta - Tr$ (see Formula 8). In the second current exchanger circuit **520**, the collector current **I15** flows into a series of diodes **23** and **24** via the PNP transistors **21** and **22** to generate a voltage at the anode of the diode **23**. While the generated voltage is given to the base of the NPN transistor **26**, a voltage generated in the diode **13** in the first current exchanger circuit **510** is given to the emitter of the NPN transistor **26** via the operational amplifier **25**.

Here, a current value for the current source **Ic3** is indicated as **Ir**, the collector

current of the PNP transistor **22** is indicated as **I22**, a voltage at the anode of the diode **13** is indicated as **V13**, and a voltage at the anode of the series of diodes **23** and **24** is indicated as **V23**. Also, the saturation current of each of the diodes and transistors is indicated as **Is**. In this case, the following formulas hold.

[Formula 14]

$$V13 = Vth \times \ln (Ir/Is)$$

[Formula 15]

$$V23 = 2 \times Vth \times \ln (I22/Is)$$

[Formula 16]

$$Vth = k \times Ta/q$$

where **k** indicates the Bolzmann's constant and **q** indicates the charge amount of an electron. Also, when the collector current of the NPN transistor **26** is indicated as **I26**, the following formula can be obtained.

[Formula 17]

$$I26 = Is \times \exp \{(V23 - V13)/Vth\}$$

Thus, based on Formulas 14, 15 and 17, the following formula can be obtained.

[Formula 18]

$$I26 = Ir \times (I22/Ir)^2$$

Also, since I22 = I15 holds, the following formula holds.

[Formula 19]

$$I22 = Ir \times \{(Ta - Tr)/Tr\}^2$$

Thus, based on Formulas 18 and 19, the following formula can be obtained.

[Formula 20]

$$I26 = Ir \times \{(Ta - Tr)/Tr\}^4$$

That is to say, an output current of the second current exchanger circuit **520** is a current in

proportion to the fourth power of Ta – Tr. Accordingly, an output current **It5** of the third current exchanger circuit **530** is a current in proportion to the fifth power of Ta – Tr.

Similarly, when Ta < Tr, the fourth, fifth and sixth current exchanger circuits **540**, **550** and **560** are operated, so that a current in proportion to the fifth power of |Ta – Tr| can be obtained as an output current **It5** of the sixth current exchanger circuit **560**.

Note that in FIG. **12**, the series of diodes **23** and **24** may be changed to have the same transistor configuration as that in FIG. **10A**, and the series of diodes **53** and **54** may be changed to have the same transistor configuration as that in FIG. **11A**.

FIG. **13** shows the detailed configuration of the crystal oscillating circuit **600** of FIG. **1**. The crystal oscillating circuit **600** of FIG. **13** is a Colpitts crystal oscillating circuit and includes a crystal resonator **601**, an NPN transistor **602**, a constant voltage supply **603**, four resistors **604**, **605**, **606** and **607**, two capacitors **608** and **609**, and a coupling capacitor **610**. Although an output voltage **Vout** is output from the collector of the NPN transistor **602** in FIG. **13**, the output voltage **Vout** can be output from the emitter of the NPN transistor **602**.

As has been described, in the temperature compensated crystal oscillator of FIG. **1**, none of the circuits including the cubic function generator **400** and the fifth-order function generator **500** requires a high voltage enough to drive a series circuit of three or more diodes. Therefore, the voltage of the power source terminal **Vcc** can be made low.

FIG. **14** shows the detailed configuration of the fourth-order function generator which can be added to the temperature compensated crystal oscillator of FIG. **1**. The fourth-order function generator of FIG. **14** is obtained by replacing the third and sixth current exchanger circuits **530** and **560** of FIG. **12** with mere current mirror circuits **535** and **565**, respectively. The fourth-order function generator of FIG. **14** is connected to current sources **Ic5**, **Ic6** and **It6** to be operated, and can generate a bidirectional current **It7**

in proportion to the fourth power of Ta – Tr in the case of Ta ≥ Tr and the fourth power of |Ta – Tr| in the case of Ta < Tr.

FIG. **15** shows a modified example of the cubic function generator **400** of FIG. **9**. The cubic function generator **400** of FIG. **15** includes a first current exchanger circuit **451**, a second current exchanger circuit **452**, a third current exchanger circuit **461**, and a fourth current exchanger circuit **462**. Each one of these current exchanger circuits **451, 452, 461** and **462** receives a current in proportion to the nth power (n is 1 or a larger integer) of Ta – Tr and outputs a current in proportion to the n+1th power of Ta – Tr, based on the same operation principle as that for the operation of the second and fourth current exchanger circuits **420** and **440** in FIG. **9**. Therefore, in the cubic function generator **400** of FIG. **15**, a bidirectional current **It4** in proportion to the cube of Ta – Tr in the case of Ta ≥ Tr and the cube of |Ta – Tr| in the case of Ta < Tr.

Note that if the number of stages in a cascade connection of the current exchanger circuits of FIG. **15** is increased, a fourth or higher order function generator can be obtained. Moreover, each of the second and fifth current exchanger circuits **520** and **550** of FIGS. **12** and **14** may be replaced with a current exchanger circuit having the same configuration as that of FIG. **15**.

As has been described, the function generator and temperature compensated crystal oscillator of the present invention can be operated at a low voltage and, therefore, is useful for portable equipment, represented by a cellular phone, and the like.